# The Solar Atmosphere at Three Temperatures during a Coronal Mass Ejection

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**Abstract.** On April 14, 1994 a major coronal mass ejection (CME) occurred while the solar atmosphere was being observed in XUV by the TEREK C instrument aboard the CORONAS spacecraft. We here compare the TEREK data before and after the CME with the Yohkoh soft x-ray data and the National Solar Observatory He I 10830 data from April 13 and 14. These three data sets provide information on structures having three different temperatures in the Sun's atmosphere. The Yohkoh and TEREK data were collected essentially simultaneously, providing a remarkable opportunity to compare high and low temperature phenomena. The expansion of the hole boundaries within the corona was directly observed using these data. The observations are interpreted in terms of low lying closed magnetic field loops before the CME and loops reconnecting higher in the corona after the CME.

## Introduction

The TEREK instrument on the CORONAS spacecraft was observing the solar atmosphere in XUV before and during the great April 14, 1994 southern polar crown CME. This CME, the subject of several other studies, was observed by Ulysses (Gosling et al., 1994) in space and was the cause of a large geomagnetic storm as reported by McAllister et al. (1996). The TEREK observations provide important new information on the solar events during this period. The TEREK XUV data are unique since no other instrument was observing at these wavelengths at the time.

The solar atmosphere was observed in XUV by the CORONAS/TEREK C instrument from 15 March to 3 July, 1994. TEREK obtained daily full Sun images in 304 Å, 175 Å and 132 Å. During the same period, the Yohkoh soft x-ray instrument was imaging the high temperature corona. Simultaneously, the He I 10830 instrument operating at the National Solar Observatory/ Kitt Peak observed at the relatively low temperatures of the chromosphere. These data sets provide an opportunity to compare CME associated changes in the corona in these three temperatures. Results of such a comparison are described here.

## The TEREK Instrument

The multi-channel telescope TEREK-C was a modified version of the TEREK telescope flown on-board the PHOBOS-1 spacecraft in 1988 (Sobelman et al., 1991; Sobelman, 1994). The telescope had two XUV channels with normal incidence multi-layer mirrors and image intensified CCD-based detectors. One of the channels incorporated the 132, 175 and 304 Å spectral bands and had a spatial resolution of 4"-16"/pixel. The other channel had a single band at 175 Å with a spatial resolution of 1'-4"/pixel. This was a considerable improvement in resolution above the PHOBOS 1 instrument. The 175 Å line is produced by Fe IX-XI. Thus observations of the 175 Å line correspond to the corona at temperatures of 1-2 MK. The 304 Å line is a blended line made up mostly from contributions from singly ionized Helium (He II) and Si XI. Singly ionized Helium, formed within the transition region at a temperature of .08- .11 MK, contributes about half the total flux.

The Si XI, formed in the corona, contributes substantial intensity to the observations and its contribution must be subtracted from the data if the He II contribution is to be studied. Sobelman et al., (1991) describe a procedure by which a relatively pure He II image can be obtained from the 304 Å and 175 Å lines. The procedure is based on the fact that the radiation from the disk contains a different spectral content from the radiation above the limb. Above the limb all of the radiation is produced in the corona. A relatively pure He II image can be obtained by subtracting the image at 175 Å, multiplied by an observationally determined factor, from the 304 Å image. Analysis of the TEREK-C data shows that this factor is different for the quiet Sun, the active Sun, and coronal holes. The "He II" data presented in this paper is the 304 Å observations corrected by using the quiet Sun factor when subtracting the Si XI contribution.

## The Sun at Three Temperatures; General Comparison

We compare the Sun as seen in three temperatures, corresponding to three regions of the solar atmosphere. The spectral lines and temperatures are given in Table 1.

Table 1.

| **Spectral line** | **source** | **Temperature (K)** | **Solar region** |
|---|---|---|---|
| **He I 10830 Å** | NSO/KP | $10^4$ | Chromosphere |
| **He II 304 Å** | CORONAS/TEREK | 0.8- 1.1 $10^5$ | Transition region |
| **Soft x-ray** | Yohkoh/SXT | 3-5 $10^6$ | Corona |

Figure 1 shows the full disk CORONAS TEREK 304 , low resolution Yohkoh soft x-ray, and National Solar Observatory/ Kitt Peak data for April 13 and 14, 1994. The Yohkoh data is shown as a negative, i. e. regions of high emission are shown as dark. The He II 304 data is treated the same as the Yohkoh data and the He I 10830 is a positive image. Thus active regions appear dark in all of the images. On April 13 the TEREK and Yohkoh data are contemporaneous and the He I 10830 Å data was collected 11 hours later. On the 14 th the TEREK data was collected 20 minutes after the Yohkoh data and the 10830 Å data 7 hours later. These nearly simultaneous observations by TEREK and Yohkoh present a rare opportunity for study. The very low resolution of the TEREK data at high northern latitudes is an artifact. The gray scales in the figures have been adjusted to aid comparison of the southern hemispheric features which are the focus of our study.

The 304 Å and soft x-ray data in Fig 1 include observations of coronal material, causing the limb of the Sun to appear somewhat indistinct. The He I 10830 Å data is from the chromosphere only so that the limb appears as a sharp line. The He II 304 Å and soft x-ray observations both show coronal material as darkening above the limbs. The relatively bright regions in the southwest correspond to the south polar coronal hole.

Although coronal holes on the disk are most easily seen in the He I data they in fact appear in all of the data sets as relatively bright areas. For example the south polar hole is seen in all of the data sets. There is a second chevron shaped hole with an apex near the equator and arms reaching both north and south. The shapes of both of these coronal holes change between April 13 and April 14, as discussed below. Also note that the boundaries of the holes were diffuse on April 13 but are generally sharp on the 14th. These changes and the associated solar event are a main focus of this report.

## A Filament

Figure 1 illustrates that, except for filaments, features in He II emission generally correlate well with features in He I absorption (Thompson et al., 1993). This correlation is demonstrated by the large active region near center meridian in all data sets. (This feature is oversaturated in the TEREK data.) However, filaments are an exception to this rule. They exhibit strong absorption in He I and weak emission in He II, i.e. they are dark in He I and are normally somewhat bright seen in He II (Harvey and Sheeley, 1997). Note the filament seen as a linear feature in the He I data to the right of the active region on both April 13 and 14. This feature seems to be completely absent in our He II observations. The temperatures at which the two helium lines are formed differ by only a factor of 10. The regions of the solar atmosphere in which these two lines are formed, the chromosphere and the transition regions, are physically close to one another. We find it remarkable that this prominence material can be kept so cool that it does not reach transition region temperatures and thus appear in He II? The mechanisms by which the He II emission and the He I absorption are produced is still not completely understood (Thompson et al., 1993), but observations such as these give important clues to the physics.

## The Solar Event of April 13-14, 1994.

On April 14 a large coronal mass ejection took place in the south polar crown causing a severe magnetic storm 68 hours later. McAllister et al. (1996) have given a detailed description of the solar events and the interplanetary manifestations. An arcade had began to form in the corona seen in soft x-rays (Yohkoh) between 0126 UT and 0238 UT April 14. The Yohkoh event began as a cusp shaped brightening of a section of the corona above the east limb in the southern quadrant at 2:38 UT, April 14. This was interpreted as field lines reconnecting after the CME left the Sun. HI 10830 (NSO/KP) ribbons of enhanced emission formed and separated, corresponding to the footpoints of the coronal arcade (Alexander et al. 1994). The arcade lengthened and widened until it extended at least 150 degrees east-west and 30 to 40 degrees north-south. A comparison of the Yohkoh data in the upper and lower panels of figure 1 shows a region of intense x-rays on April 14 that appears only as a diffuse region of low emission on the 13th. The changes in the arcade seen in soft x-rays were rather rapid for about 8 to 10 hours. Slower changes continued for at least another day. Most of the rapid changes had been completed when the He II 304 Å (TEREK) data in figure 2 were collected. Since the soft x-ray and He II 304 Å data sets were taken simultaneously or almost so, they can be directly compared in detail. We do not make detailed comparisons with the KPO He I data because they were observed several hours after the TEREK/Yohkoh data on each day. We note however that the small differences in the coronal hole boundaries as seen in

He II and He I can be easily accounted for by the difference in the time at which the observations were taken.

**Comparison of coronal hole boundaries seen in Yohkoh and TEREK data.**

The simultaneous observations of He II and soft x-rays on April 13 and April 14 gives a unique opportunity to make a detailed comparison of solar atmospheric structures seen at two different temperatures (heights). Figures 2 and 3 shows detailed data from April 13 and 14 respectively. The x-ray data have been smoothed and the color table has been selected to facilitate comparison. The axes give the positions of features in arcsec measured from an arbitrary point. The x-ray data is on a log scale and the He II data on a linear scale, preventing quantitative comparisons. The Yohkoh data shows brightening above the solar limb at the bottom of the figures. A comparison of fig. 2 with fig. 1 will allow the region of the Sun shown to be identified.

On April 13 the contemporaneous x-ray and He II data are dissimilar. The soft x-ray data shows the south polar hole and the southern extension of the equatorial hole. Between, there is diffuse band of enhanced x-ray emission which corresponds to a region of magnetic field loops that do not extend into interplanetary space, i.e. the magnetic field is closed. The boundaries of the closed region are not clearly delineated. The intensity of the x-ray emission gradually increases to a maximum at about the point (100, 550). A second maximum is near (700, 30). The emission is less intense for values of the abscissa

> 800 arcsec. The He II data show both similarities and important differences. There is a broad band containing structures with relatively intense emission, indicating closed field lines. The boundaries of the of the south polar hole and equatorial hole can be discerned but they are diffuse in these data as well. The width of the closed region is estimated to be about 25 % broader in He II from the transition region than in x-rays from the corona (see also Obridko et al., 1997). This may be due to the super-radial expansion of the coronal holes that bound the closed region. The x-ray emission is strongest in the center of the closed region but the He II emission is relatively uniform, although perhaps strongest near the closed region southern boundary. This suggests that there are closed loops throughout the region with some loops reaching into the low corona. Note also the large differences between the x-ray and He II emission for values of the abscissa >800 arcsec. In that area there is strong He II emission and only weak x-ray emission suggesting that the region contained cool low lying closed arcades.

Fig. 3 shows He II and x-ray data taken at almost simultaneously on April 14. The region of He II emission is about 15% wider than it was before the CME, indicating that some field lines that had previously been within the holes are now closed. The resemblances between the data sets in fig. 3 are striking. The boundaries of the closed region are now clearly defined in both data sets. The region for abscissa >800 that was bright in He II but darker in x-rays is now bright in both emissions, indicating the loops now extend to higher altitudes. The emissions are strongest near the boundaries of the closed region in both data sets, consistent with arcades being heated by reconnection high in the corona.

We are seeing the footpoints of the lines. Most important however is the fact that the width of the region seen in He II is the same as the width seen in soft x-rays. This is interpreted as due to the CME stretching the closed region out into the corona and subsequent reconnection of field lines higher in the corona; simultaneously decreasing the super-radial expansion of the coronal holes.

**Conclusions:**

- The filament was a chromospheric structure~~s~~ and did not reach transition region temperatures. This phenomen~~a~~on is not currently understood and further studies are underway.
- During the quiet solar conditions that preceded the CME the magnetically closed region was about 25 % wider at chromospheric temperatures than at the coronal temperatures detected by Yohkoh, reflecting super-radial expansion of the coronal holes.
- After reconnection of magnetic field lines following this major coronal mass ejection closed regions structure became more nearly the same when seen in the two temperatures. In particular they had the same width, reflecting the extension of the coronal arches to higher altitudes and the heating of newly reconnected field lines.

This study demonstrates that the expansion of coronal holes in the corona can be directly observed by comparing coronal soft x-ray observations with simultaneous transition region He II 304 Å observations. Studies of these data sets combined with observations of the solar wind will provide an important tool for studying the effects of super-expansion on solar wind acceleration.

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**Figure Captions**

1. Full disk observations of the Sun on April 13 (upper panel) and April 14 (lower panel). The leftmost images in each panel are the TEREK images (temperature $10^5$ ), the center images are the Yohkoh images (temperature ~4x $10^6$ ) and the rightmost images are the NSO/KP images (temperature $10^4$ K). The time the observation was taken is given below each image. The blurring of the TEREK images in the northern hemisphere is an artifact.

2. Soft x-ray data from Yohkoh (top panel) and He II XUV data from Coronas (bottom panel) data for April 13, 1994. The axes are labeled in arbitrary units. The color tables have been adjusted to ease comparison. Emissions from the solar corona show as brightening below the limb that can be discerned as arc just above the lower boundary of the Yohkoh pictures. In the x-ray data the predominantly yellow and green regions are believed to be magnetically closed, and the dark blue regions open. In the He II data the red, yellow and green regions are believed to be closed and the light and dark blue open.

3. The same as figure 2 but for April 14, 1994.

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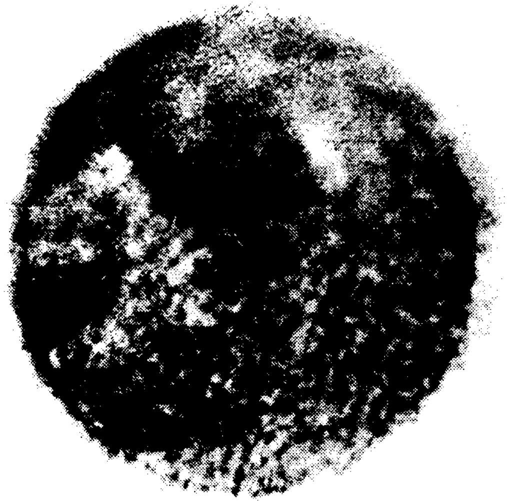

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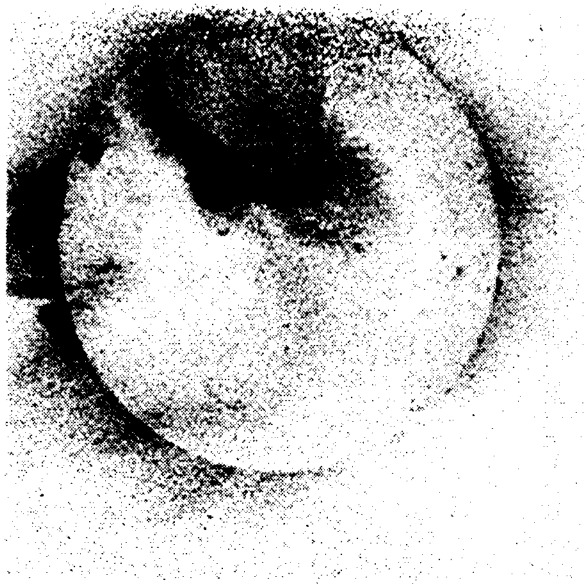

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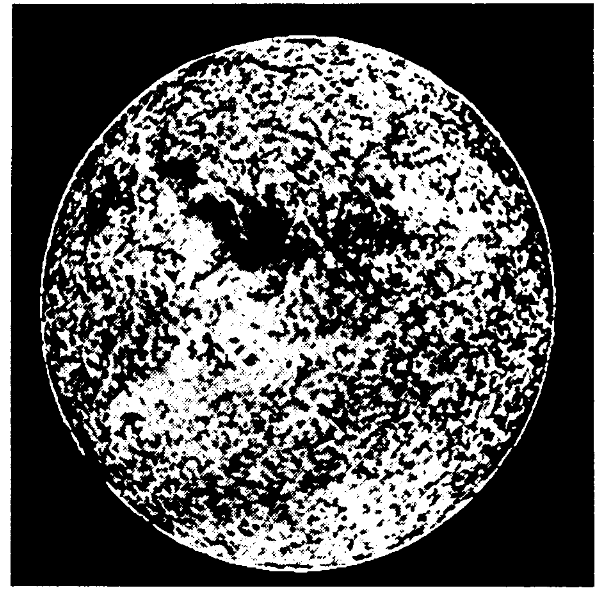

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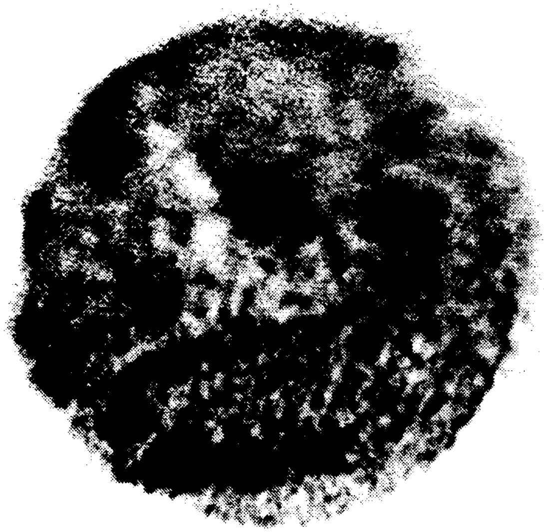

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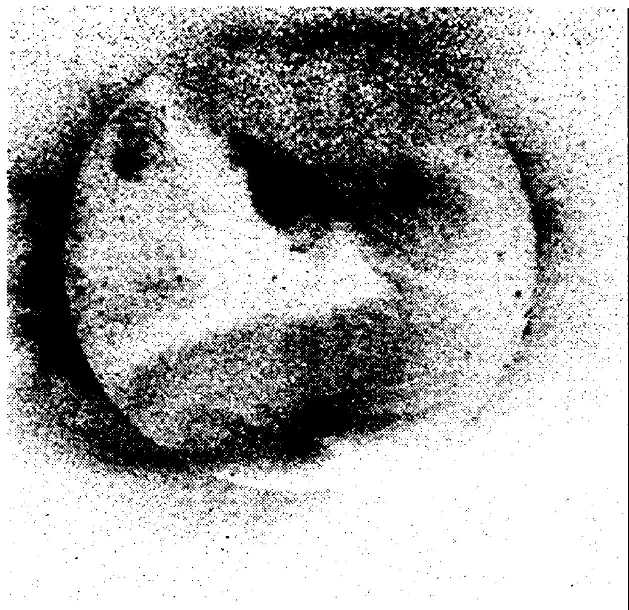

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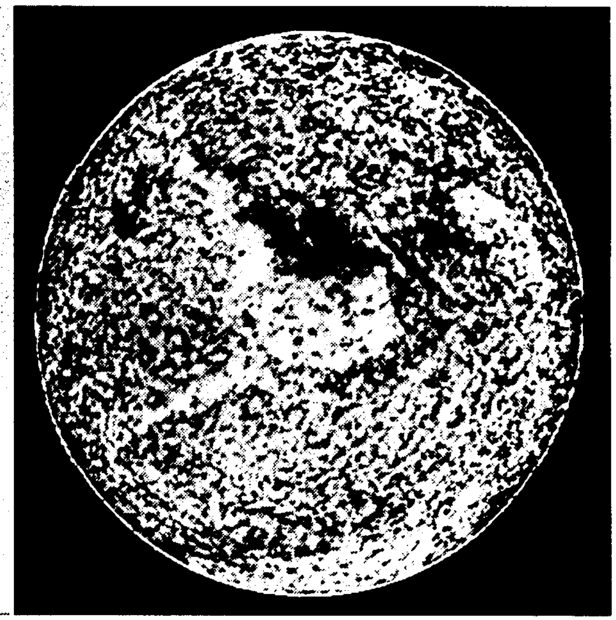

HeI 4/14/94 18:33-19:13

fig 1

Yohkoh, April 13, 1994

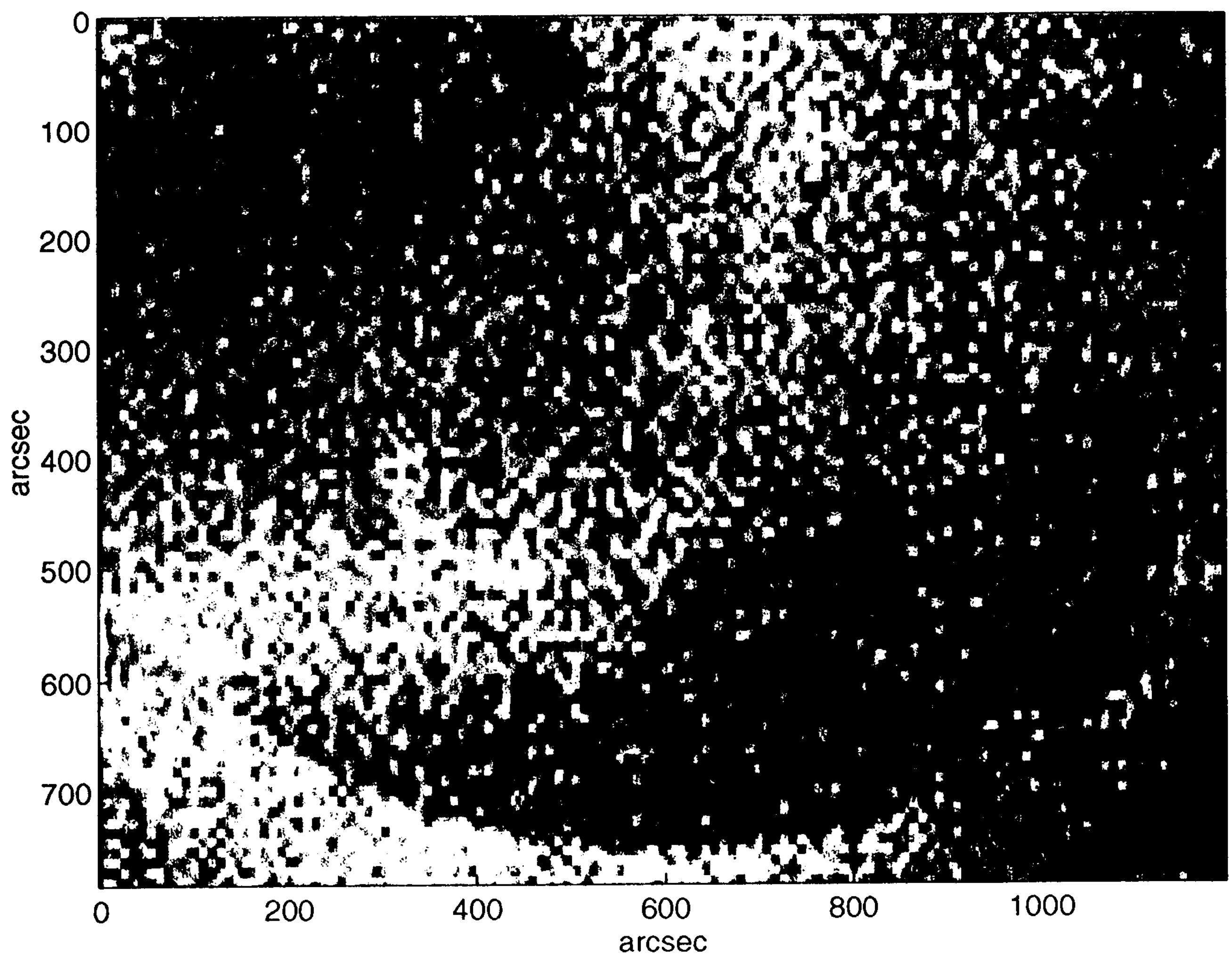


fig 2, top

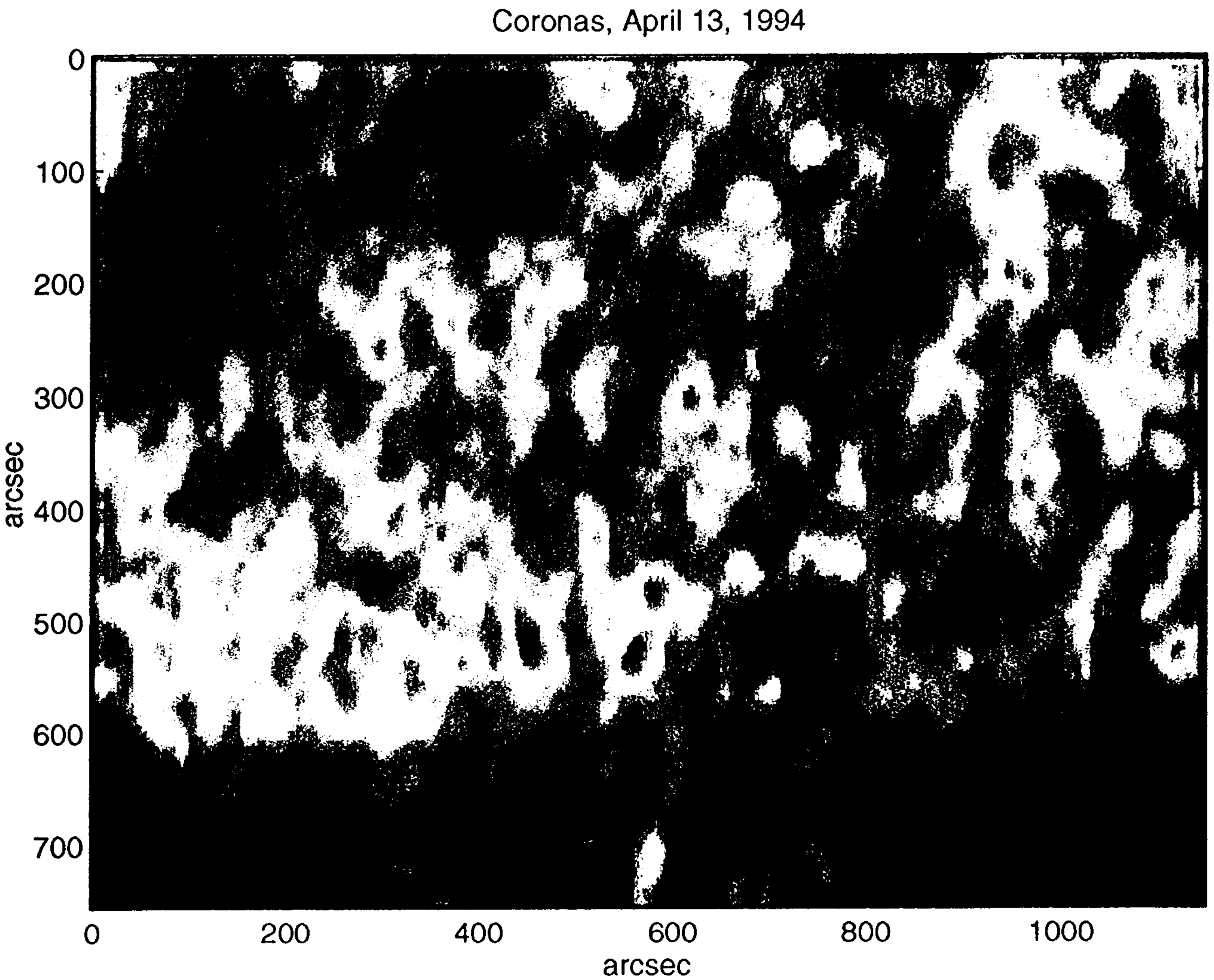
Coronas, April 13, 1994
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Fig 2 Bottom

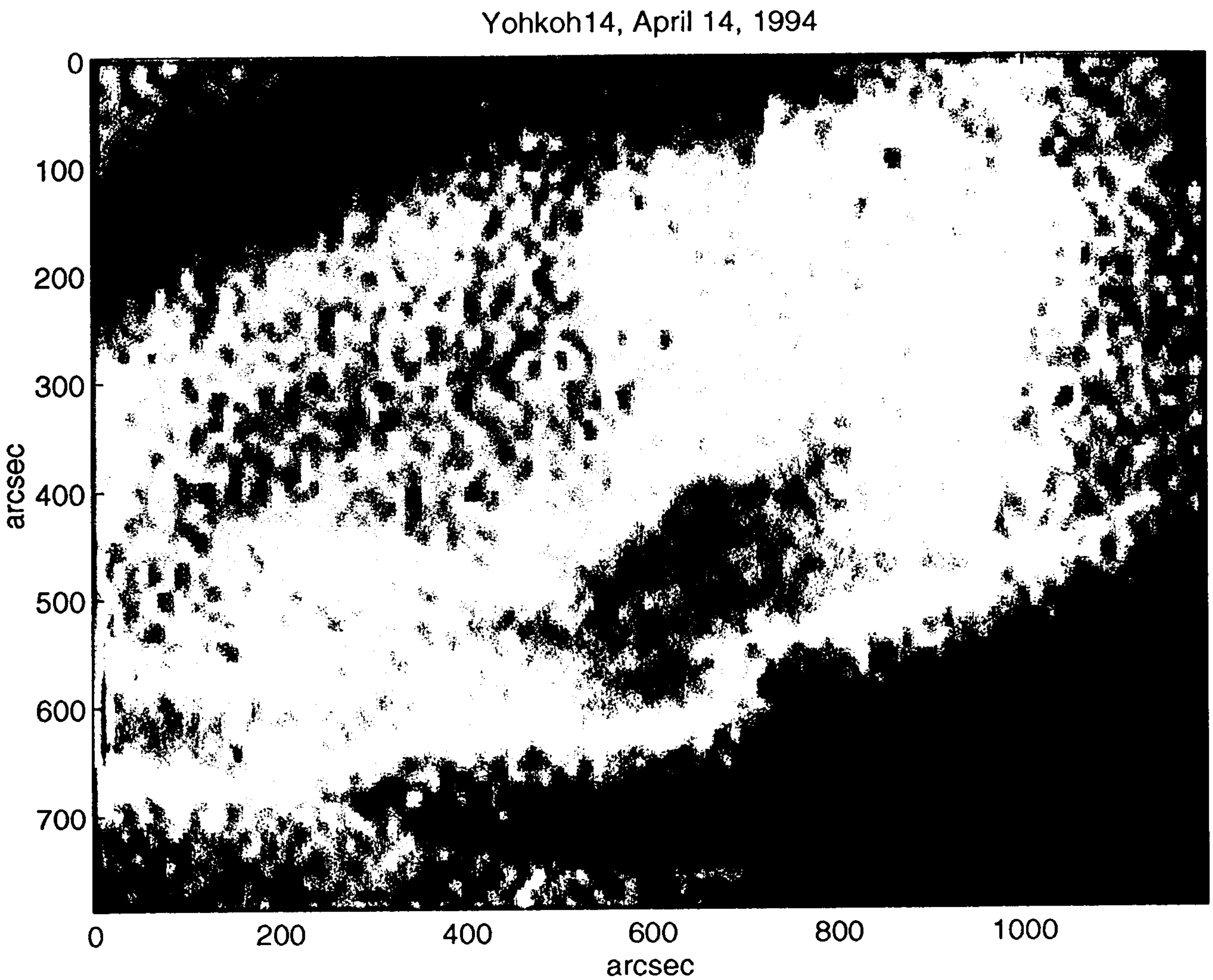
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Fig 3 top

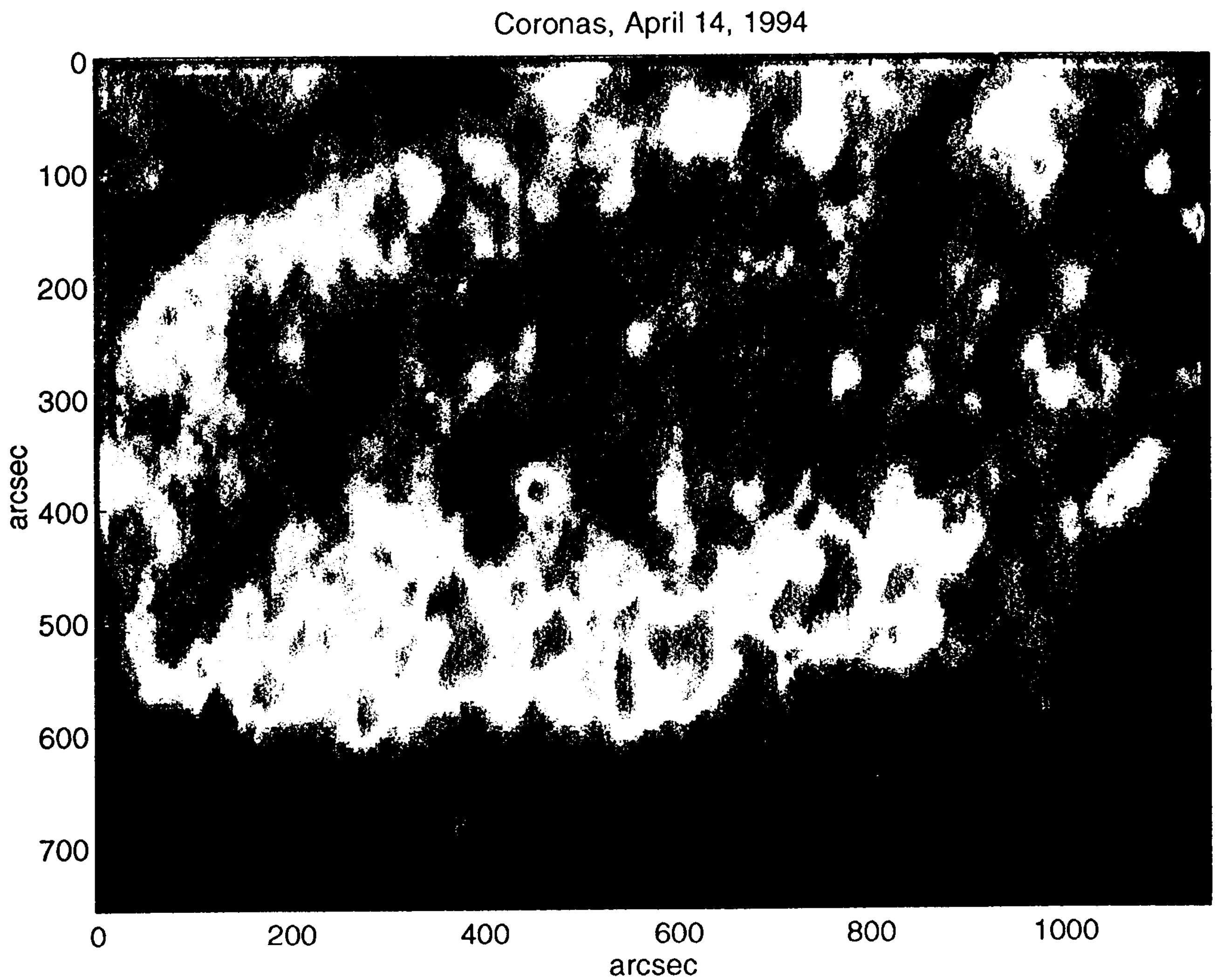
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Fig 3, bottom